Off
Axis

Physics Potential

Cambridge Off-Axis Meeting
12 January 2004

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Off Axis

$P(\nu_\mu \rightarrow \nu_e)$ (in Vacuum)

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$
  - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$
  - $P_3 = \mp J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$

where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \times$

$\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$

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$P(\nu_\mu \rightarrow \nu_e)$ (in Matter)

- In matter, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

$$E_R = \frac{\Delta m_{13}^2}{2\sqrt{2} G_F \rho_e} \approx 11 \text{ GeV for the earth's crust.}$$

About a ±23% effect for NuMI, but only a ±10% effect for JPARC .

Magnitudes

- For long-baseline $\nu_\mu \rightarrow \nu_e$ oscillations, P_1, P_3, P_4, and the matter effects are all the same order of magnitude.
- A measurement of $P(\nu_\mu \rightarrow \nu_e)$ measures "$\sin^2(2\theta_{13})_{eff}$" which is only a crude estimate of $\sin^2(2\theta_{13})$.
- Reactor experiments measure $\sin^2(2\theta_{13})$ directly, but have no sensitivity to sign($\Delta m_{13}{}^2$) or δ.

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Probability Plots

- **Probability plots assumes a particular result for a measurement of P($\nu_\mu \to \nu_e$) and show**
  - **The possible values of sin^2(2θ_{13}), sign(Δm_{13}^2), and δ consistent with this measurement, and**
  - **How another another measurement would discriminate among them.**

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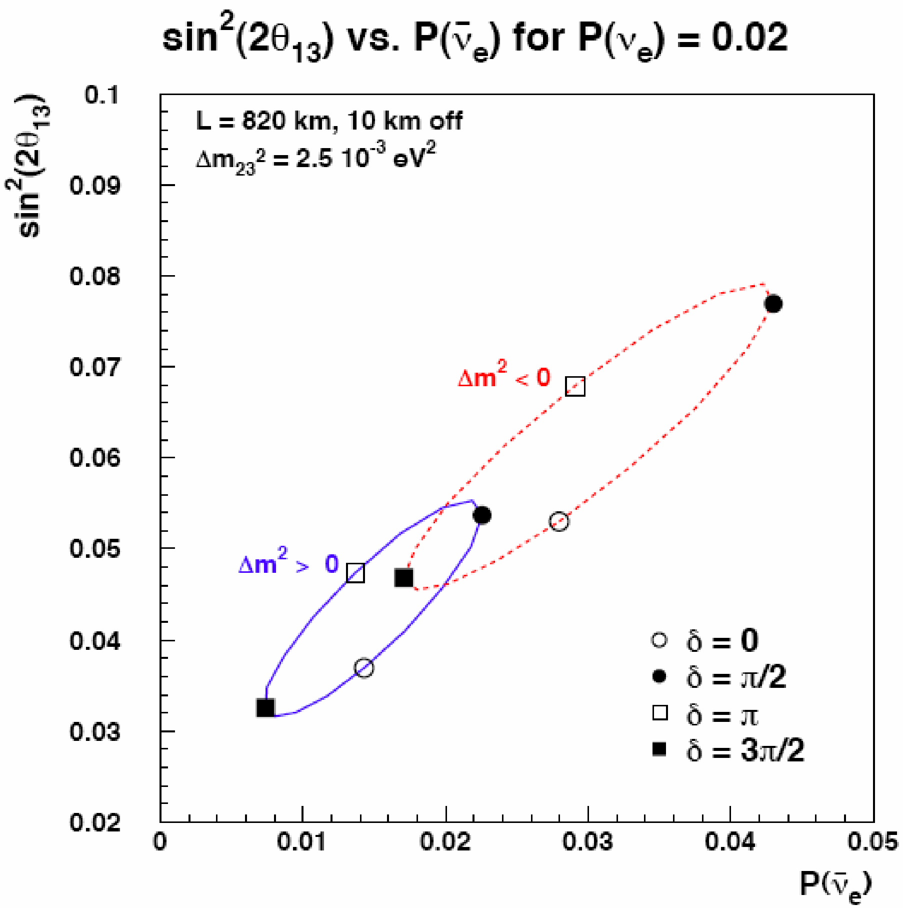
$P(\nu_\mu \to \nu_e) = 0.02$ at 820 km



Note

(1) Effect of $\cos(\delta)$ term

(2) Ambiguities

(Hidden ambiguity: P1 $\propto \sin^2(\theta_{23})$; if $\sin^2(2\theta_{23}) = 0.95$, $\sin^2(\theta_{23}) = 0.39$ or 0.61)

(1) Rough equivalence of reactor and antineutrino measurements

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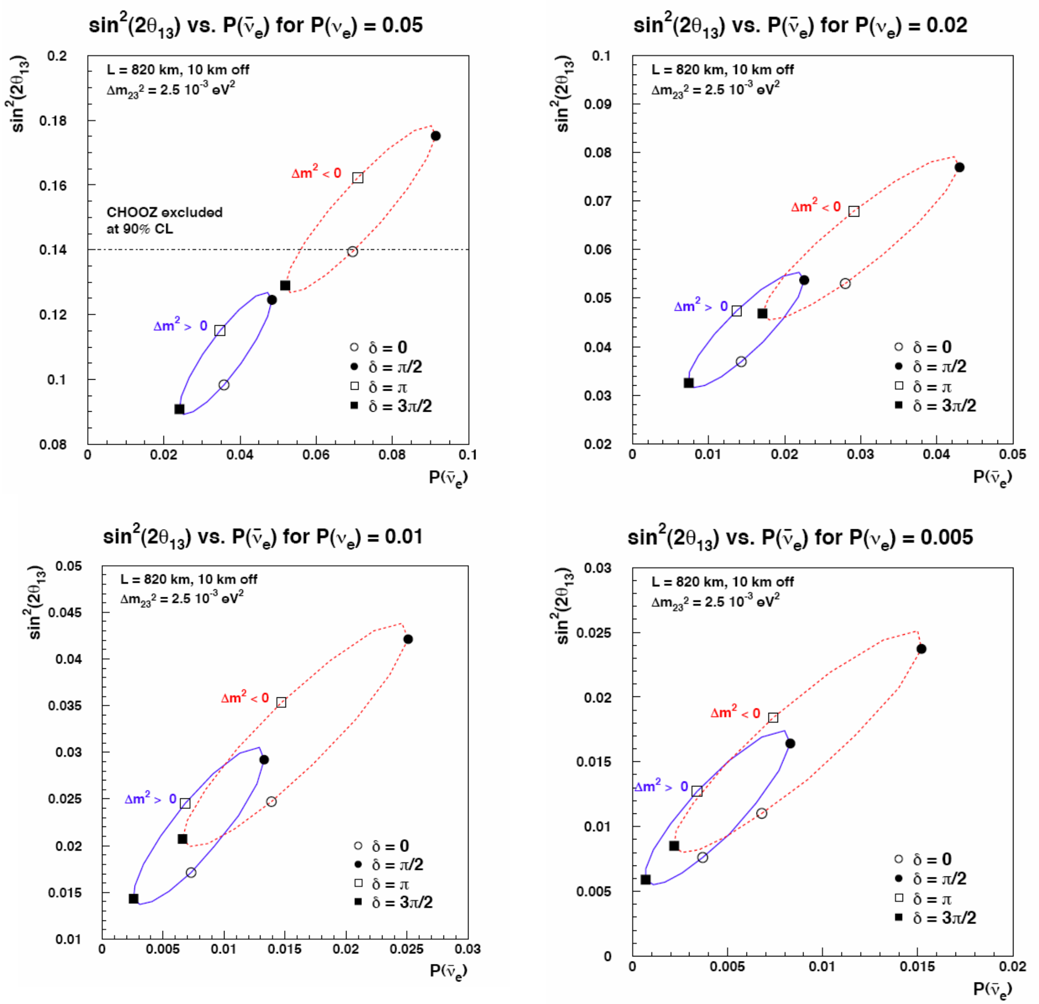
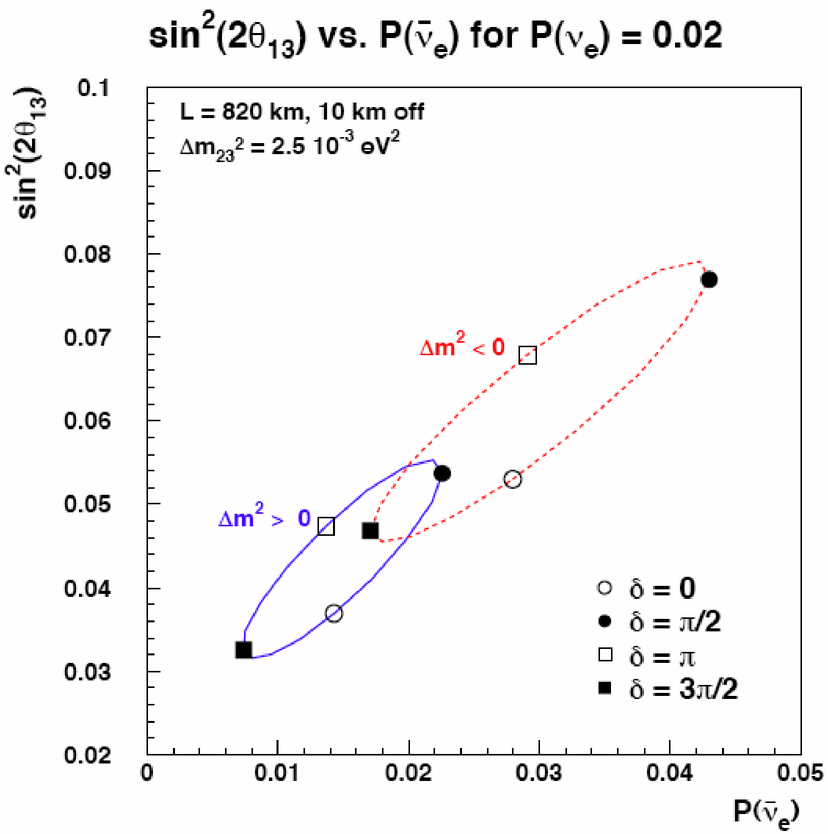
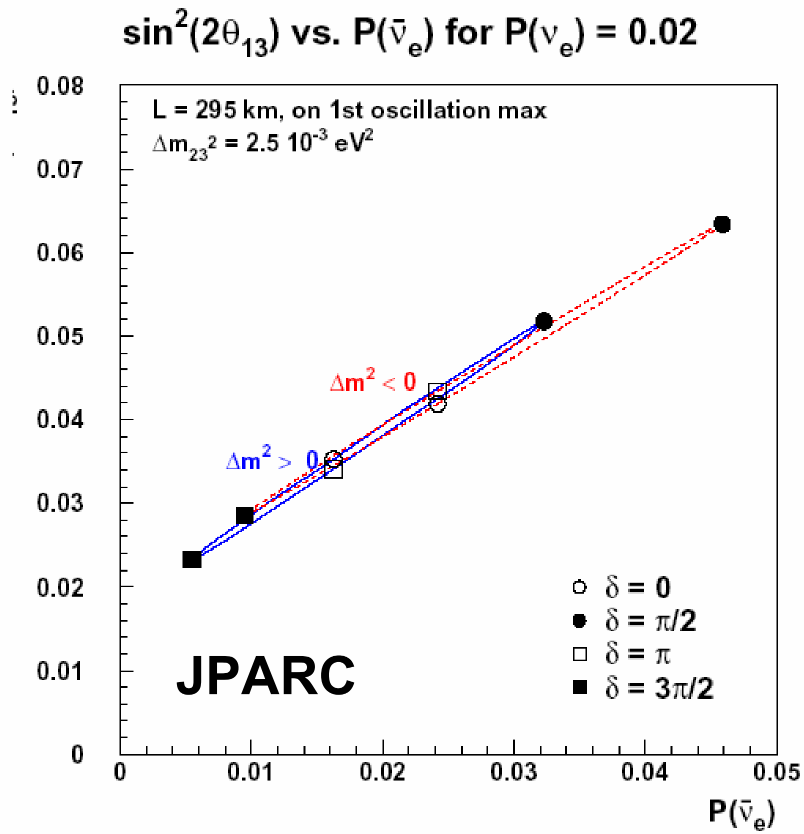
$P(\nu_\mu \rightarrow \nu_e)$ = 0.05, 0.02, 0.01, and 0.005 at 820 km



$P(\nu_\mu \rightarrow \nu_e) = 0.02$ at 820 and 295 km





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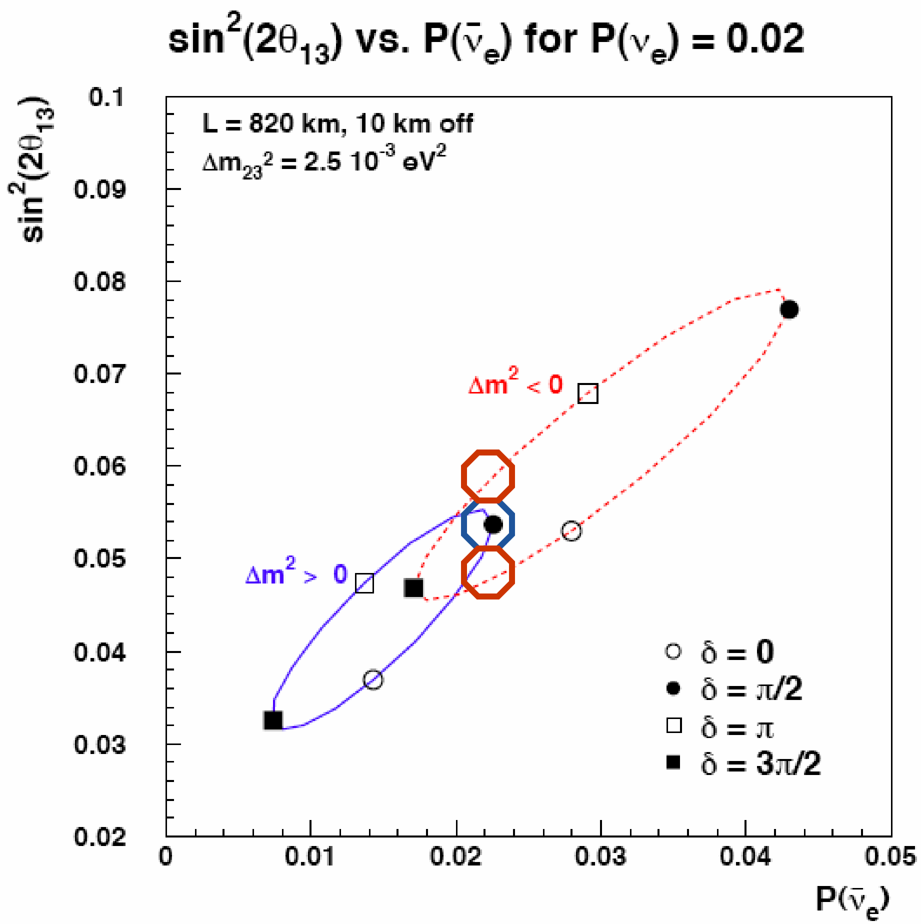
$P(\nu_\mu \to \nu_e) = 0.02$ at 820 km

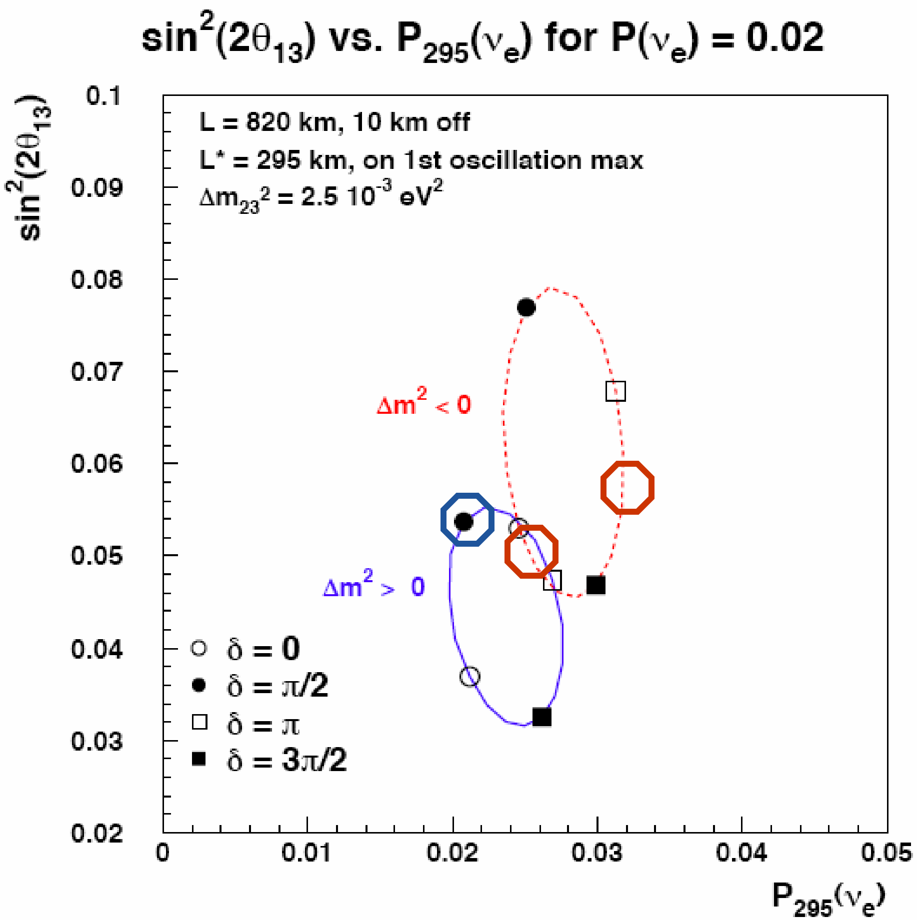


Note ambiguities between normal hierarchy and inverted hierarchy.

Can combining JPARC and NuMI data help?

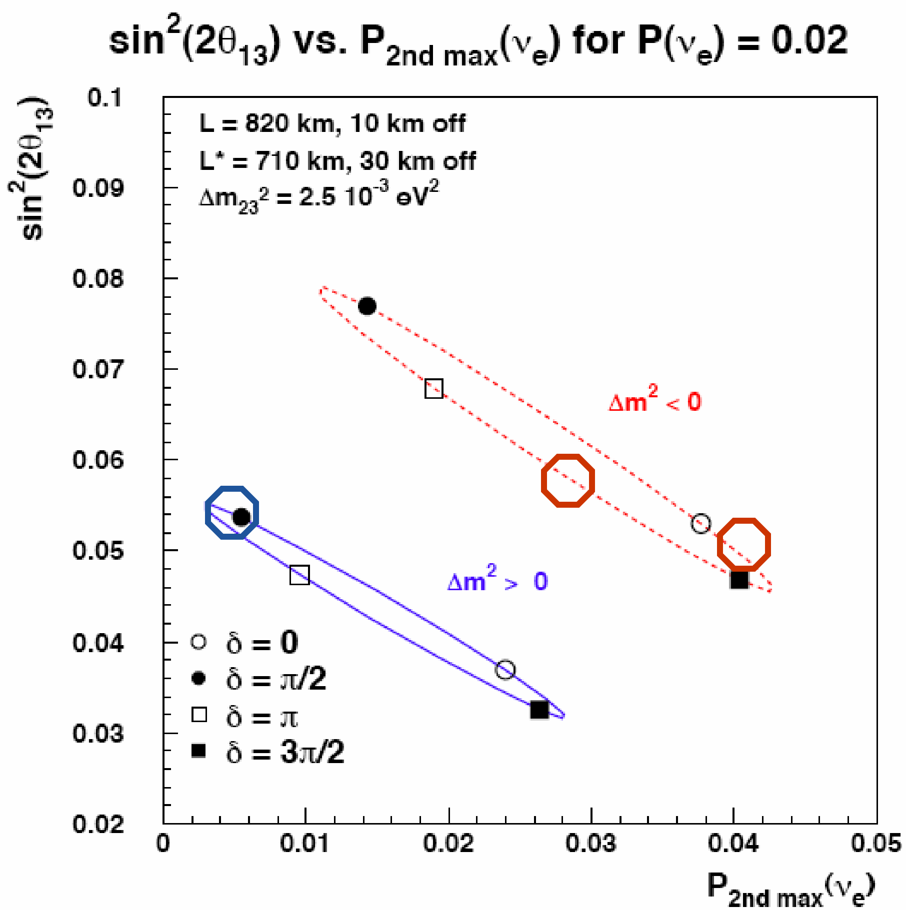
$P(\nu_\mu \to \nu_e) = 0.02$ at 820 km vs. $P(\nu_\mu \to \nu_e)$ at 295 km

Off Axis



Ambiguous points are still fairly close together

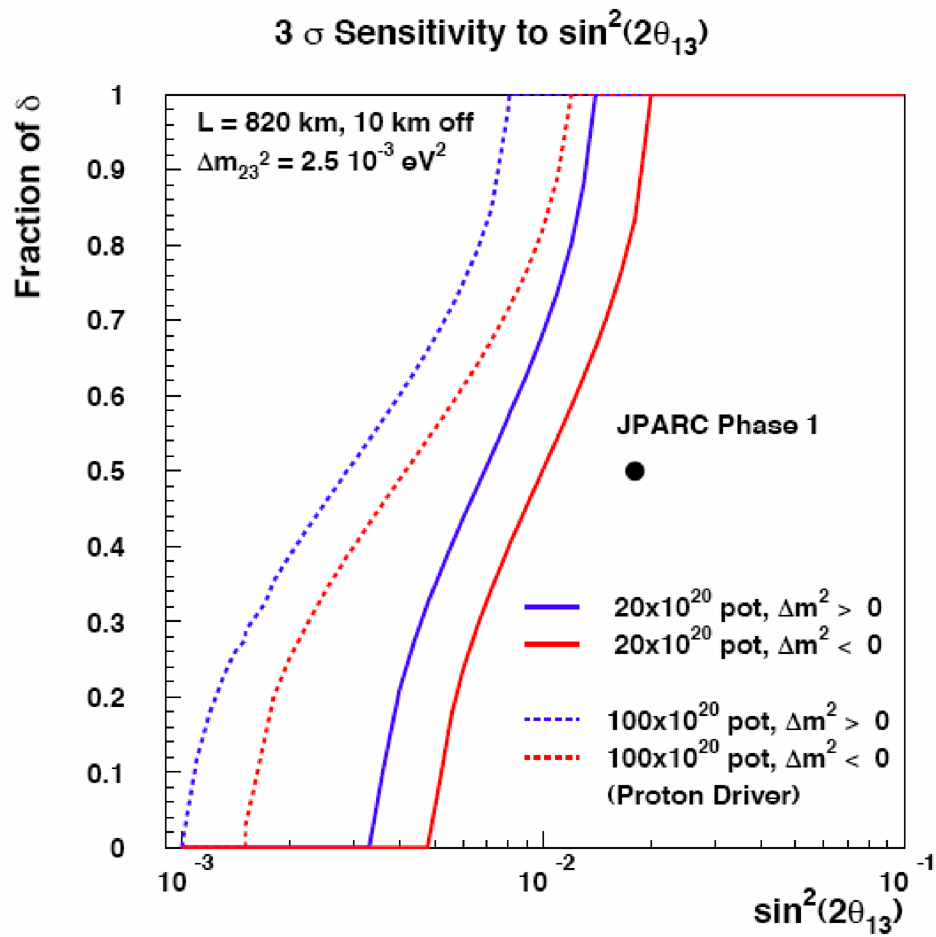
A 2nd Detector at the 2nd Maximum?



Goals of the Off-Axis Experiment

- Primary goal: Find evidence for $\nu_\mu \rightarrow \nu_e$, determining $\sin^2(2\theta_{13})$ to a factor of 2.
- Longer term goal: Determine the mass hierarchy.
- Ultimate goal: Precision measurement of the CP-violating phase δ.

3 σ Discovery Potential for $\nu_\mu \rightarrow \nu_e$



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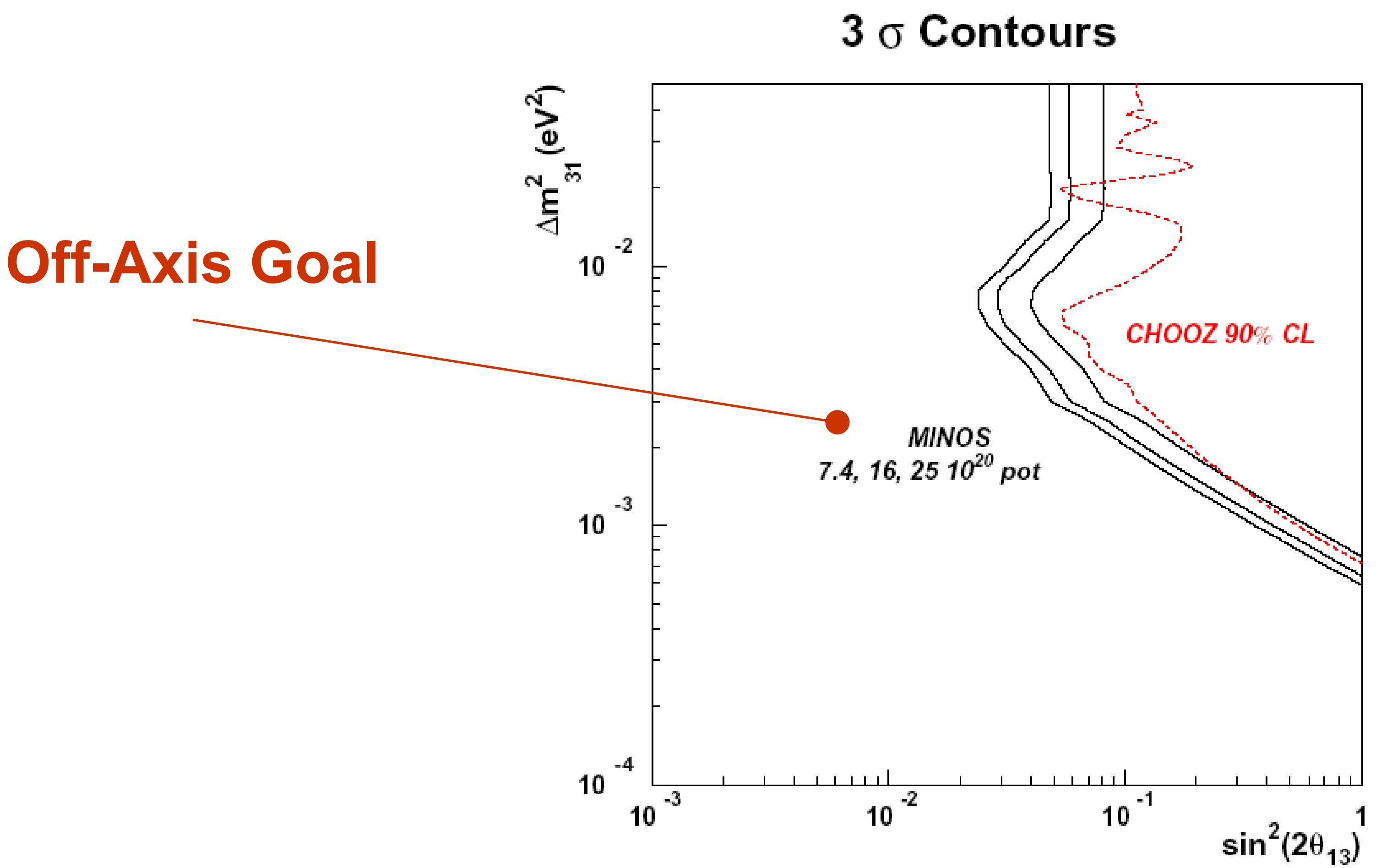
MINOS Sensitivity to $\nu_\mu \rightarrow \nu_e$ at 3σ Discovery



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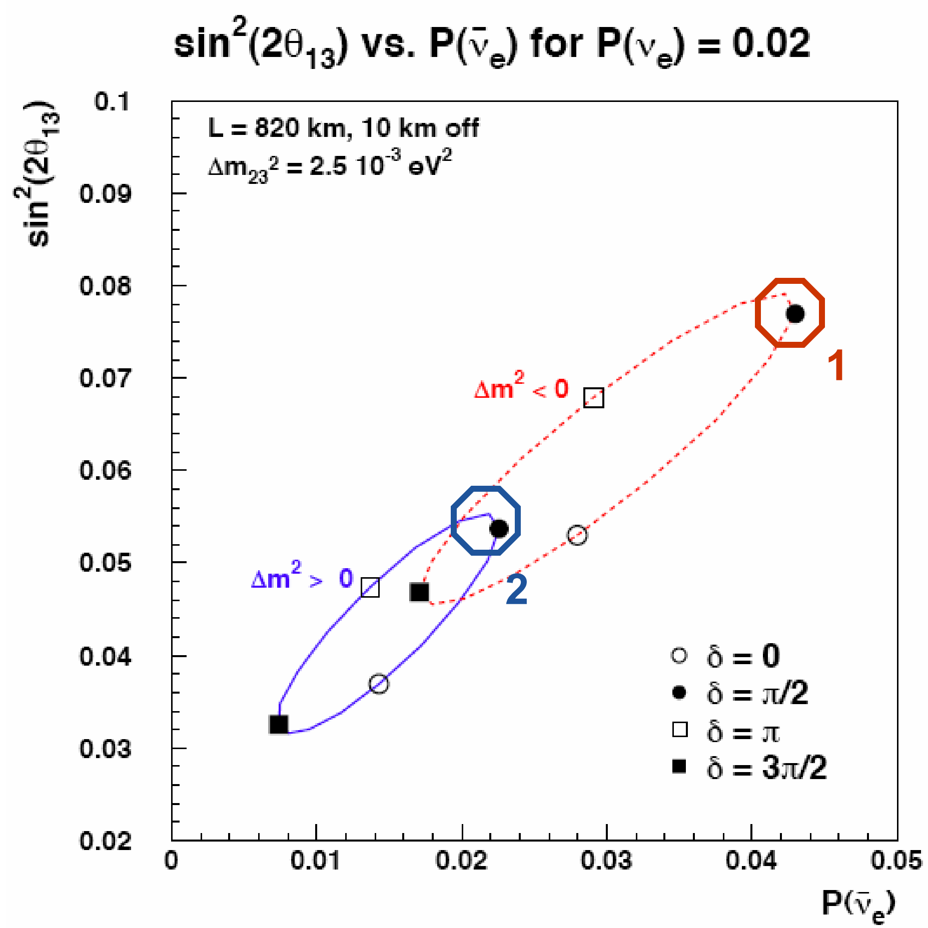
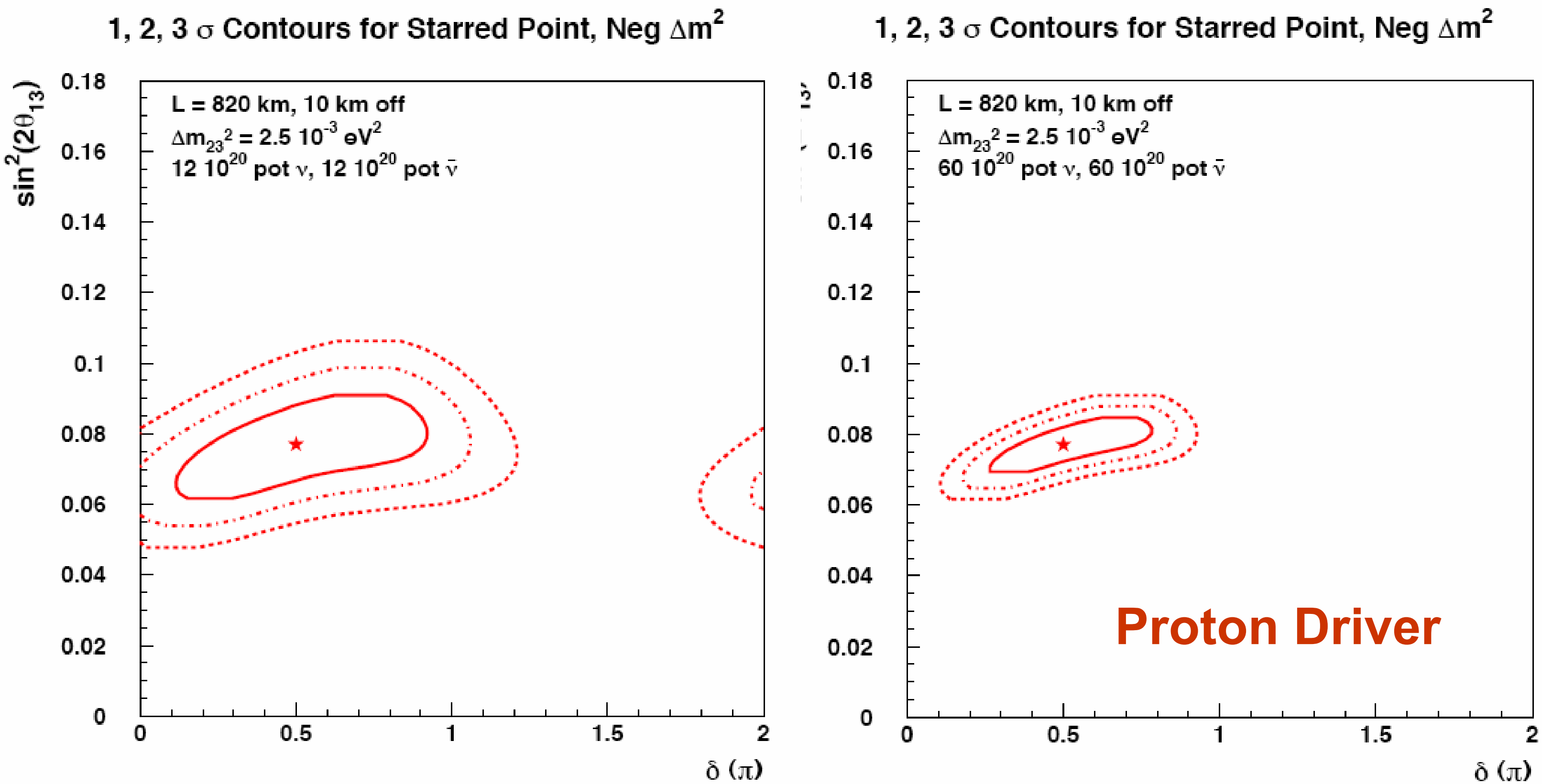
Sensitivities

- **To consider sensitivities, I consider one experiment (or one set of experiments) with the expected results and calculate 1, 2, and 3 σ contours based on $\Delta\chi^2$'s, assuming 5% systematic error on the background.**

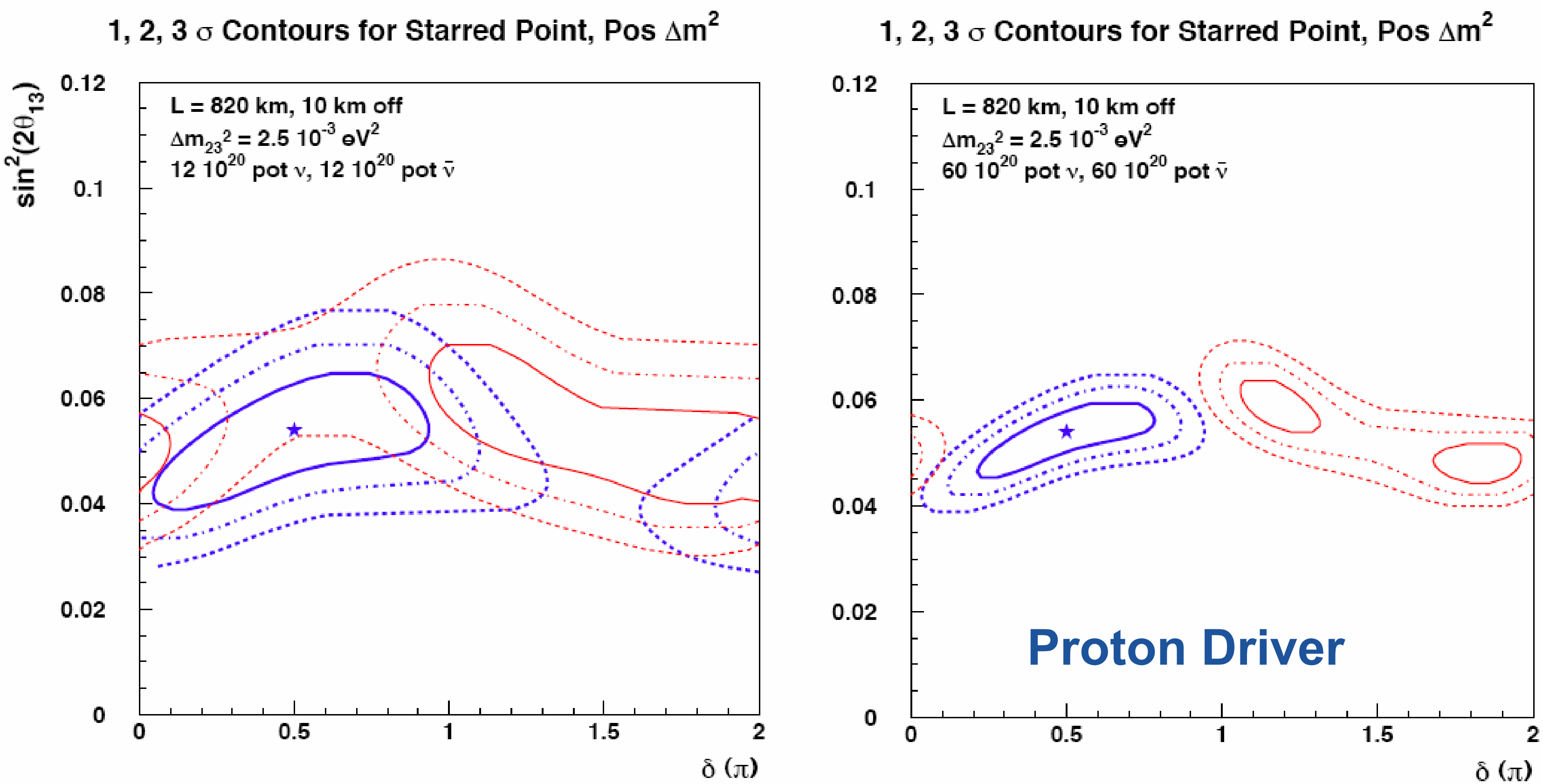
Study Points



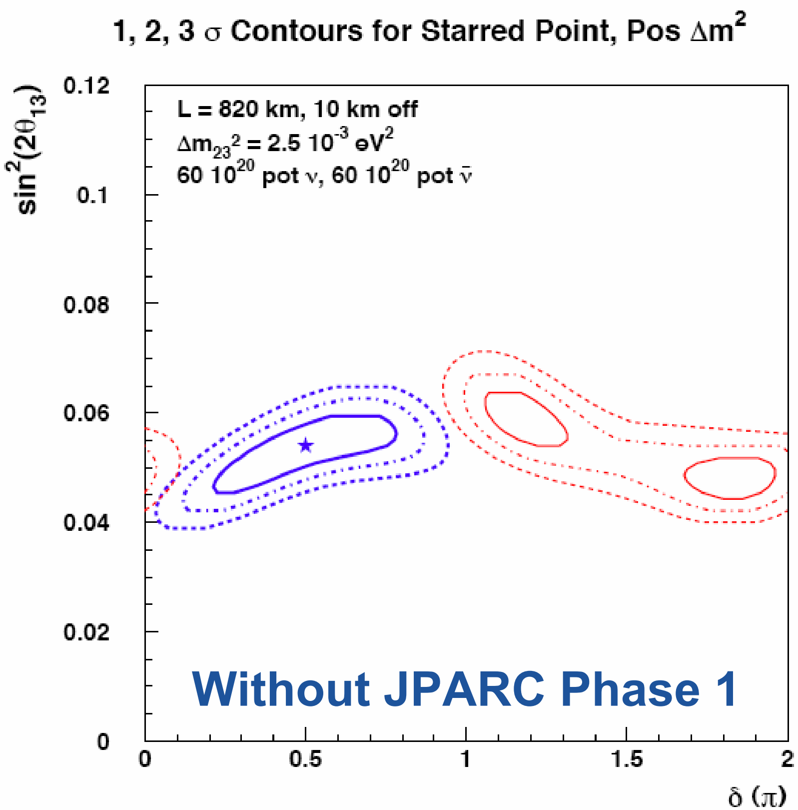
Point 1: NuMI 3 yr ν, 3 yr $\bar{\nu}$ $4\ 10^{20}$ and $20\ 10^{20}$ pot/yr

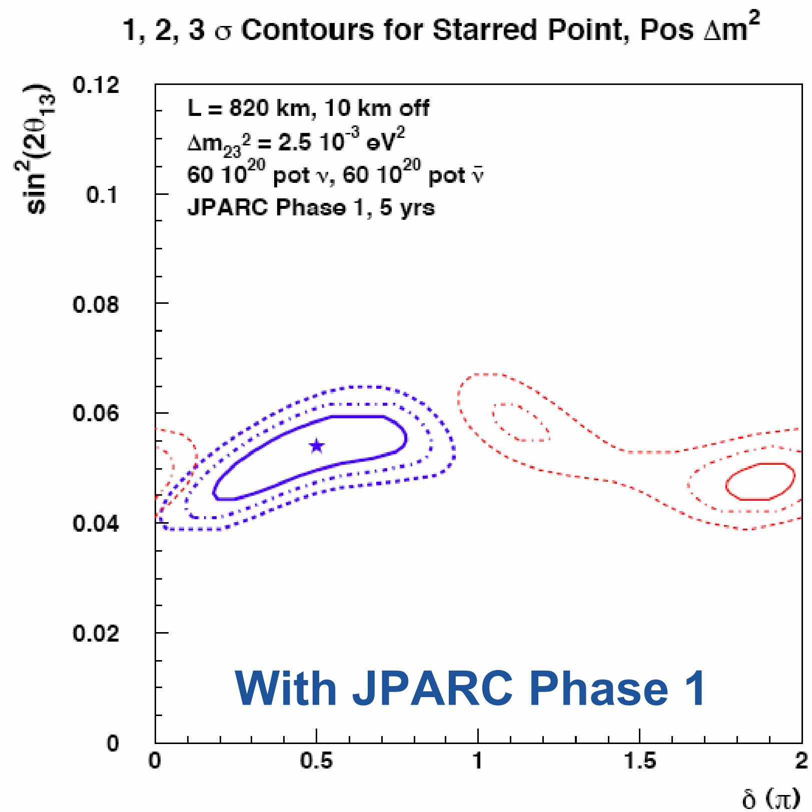


NuMI 3 yr ν, 3 yr $\bar{\nu}$ 4 10^{20} and 20 10^{20} pot/yr



NuMI 3 yr ν, 3 yr $\bar{\nu}$, 20 10^{20} pot/yr and JPARC, Phase 1





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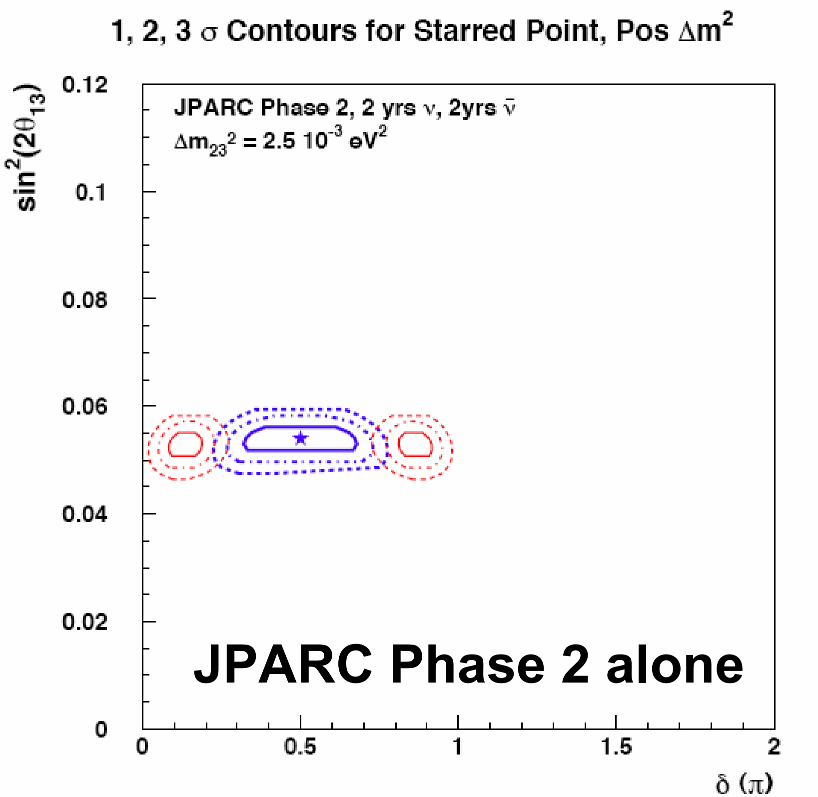
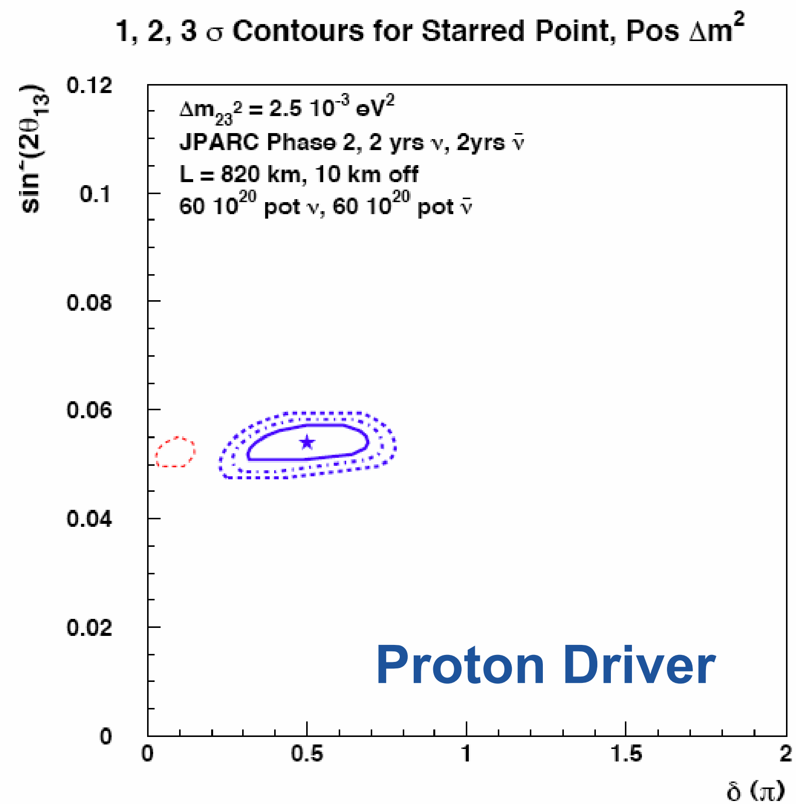
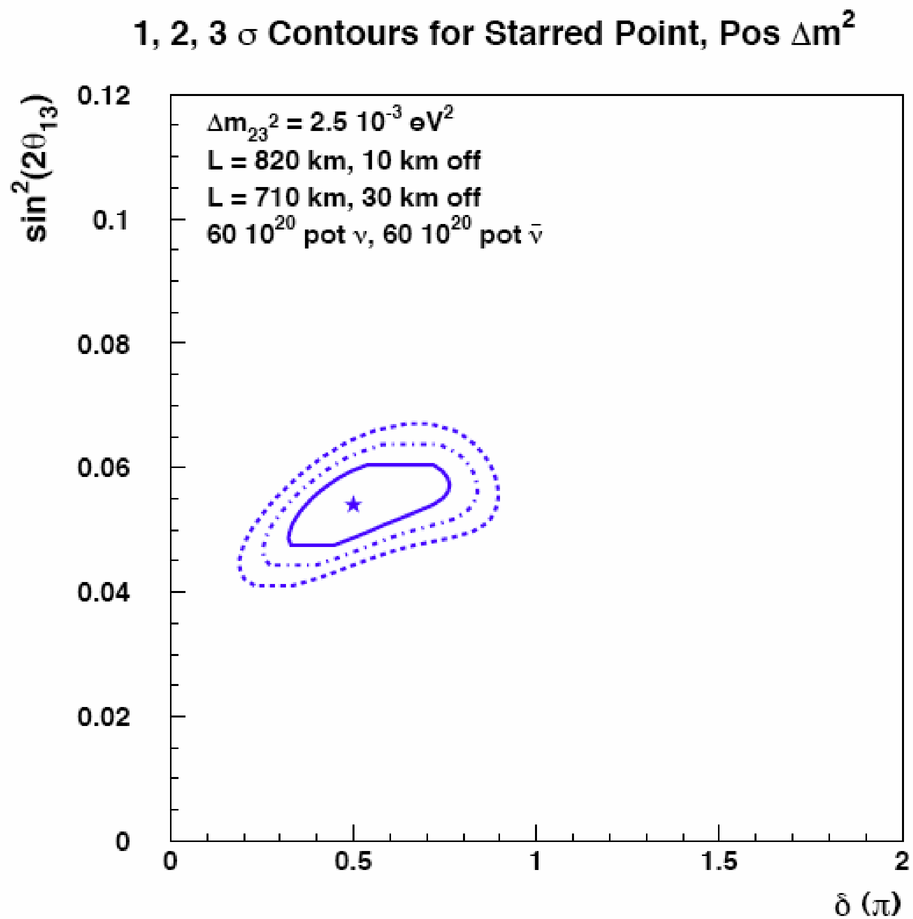
NuMI 3 yr ν, 3 yr $\bar{\nu}$, 20 10^{20} pot/yr and JPARC Phase 2, 2 yr ν, 2 yr $\bar{\nu}$

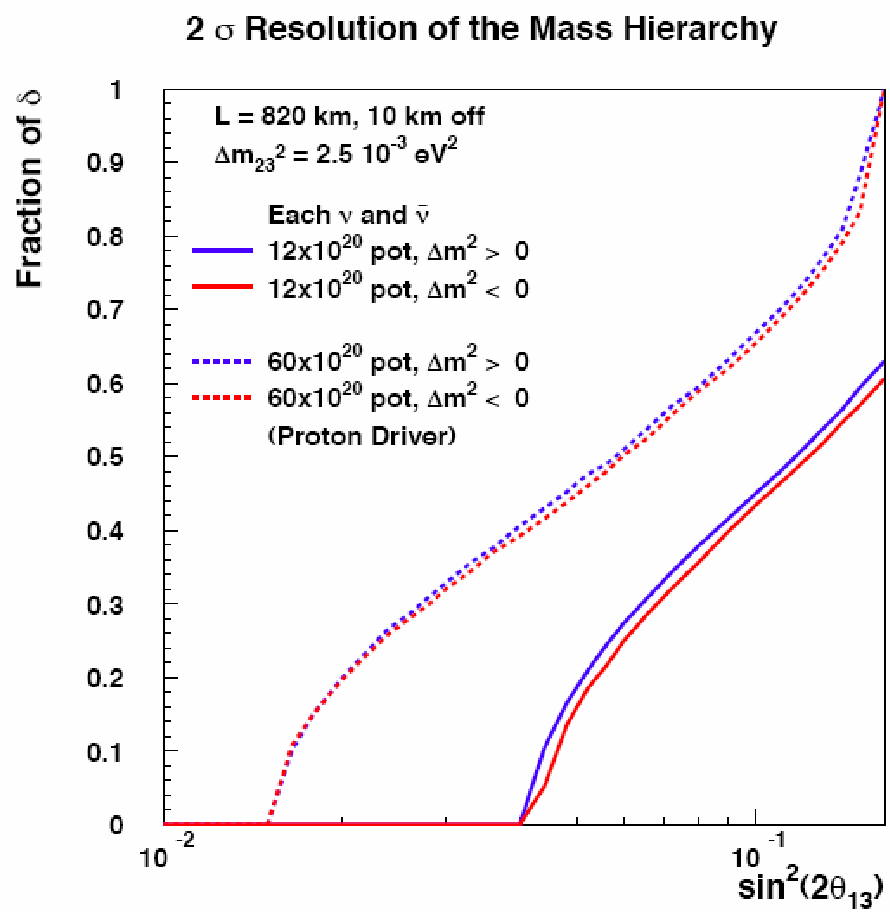




NuMI 3 yr ν, 3 yr $\bar{\nu}$, 2 Detectors and Proton Driver



95% CL Resolution of the Mass Hierarchy



95% CL Resolution of the Mass Hierarchy with 2 Detectors